Pulsar Variability and the Global Magnetosphere

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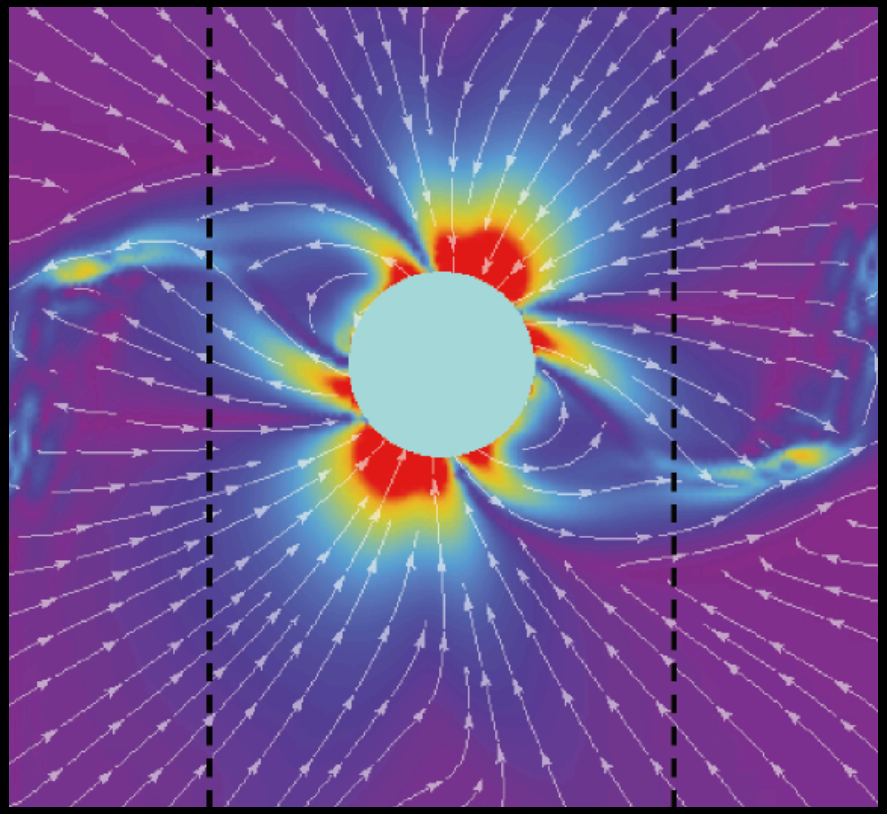
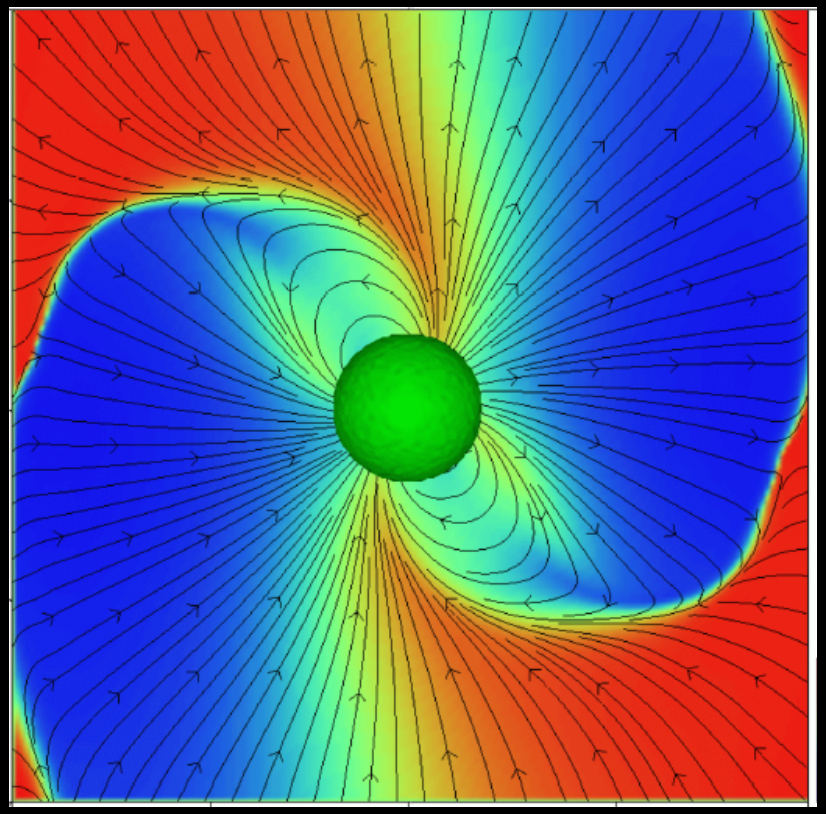




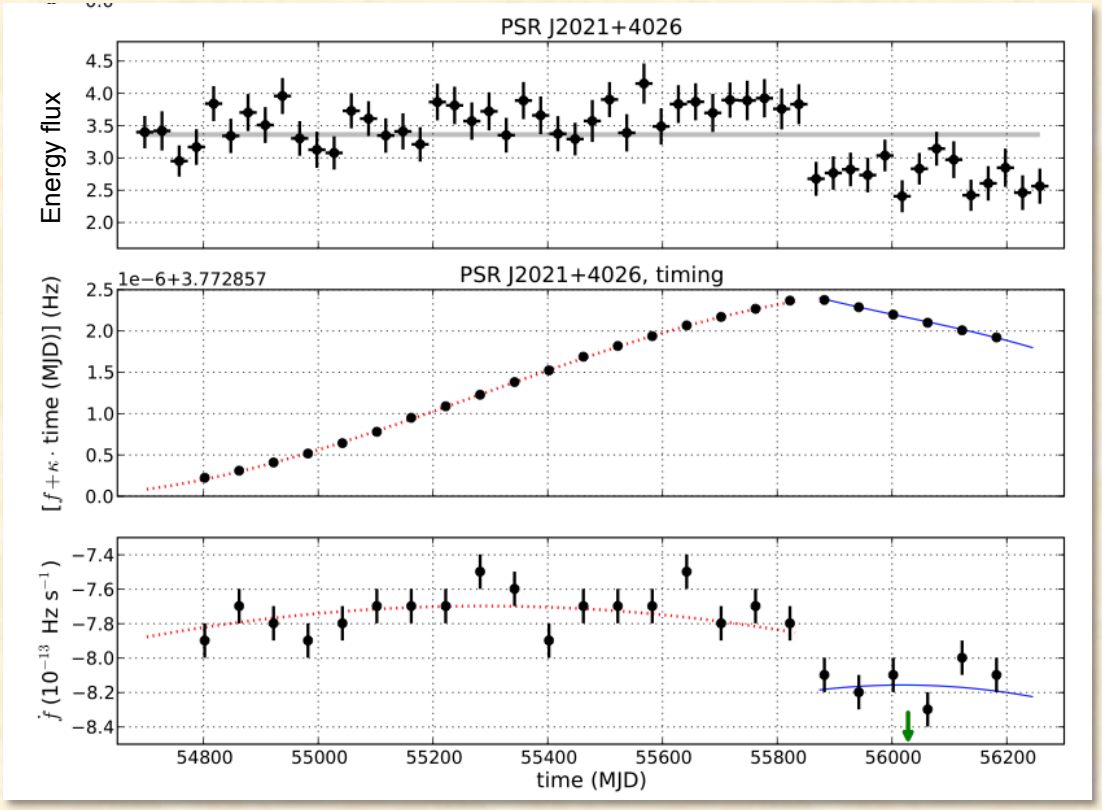
Observed pulsar variability

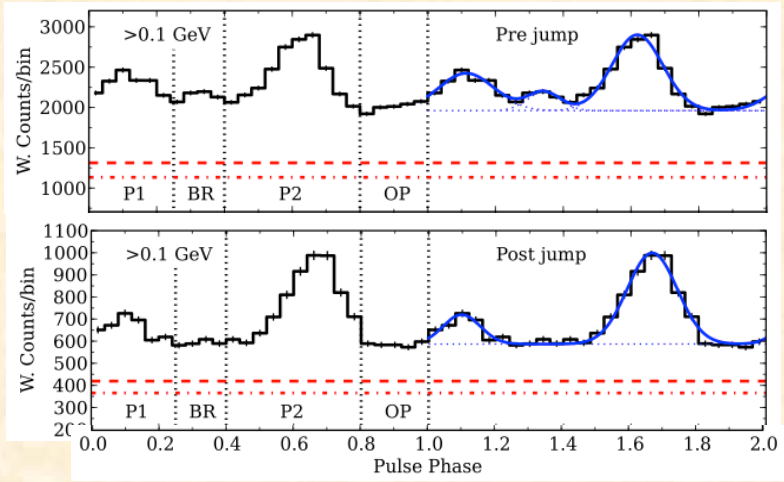
- Spin-down state changes (γ-ray, X-ray and radio)
- Mode switching
- Intermittent pulsars
- [Glitches]

Spin-down state changes - γ-ray PSR J2021+4026

Simultaneous decrease in γ-ray flux (20%) and increase in spin-down rate (4%)

Allafort et al. 2013

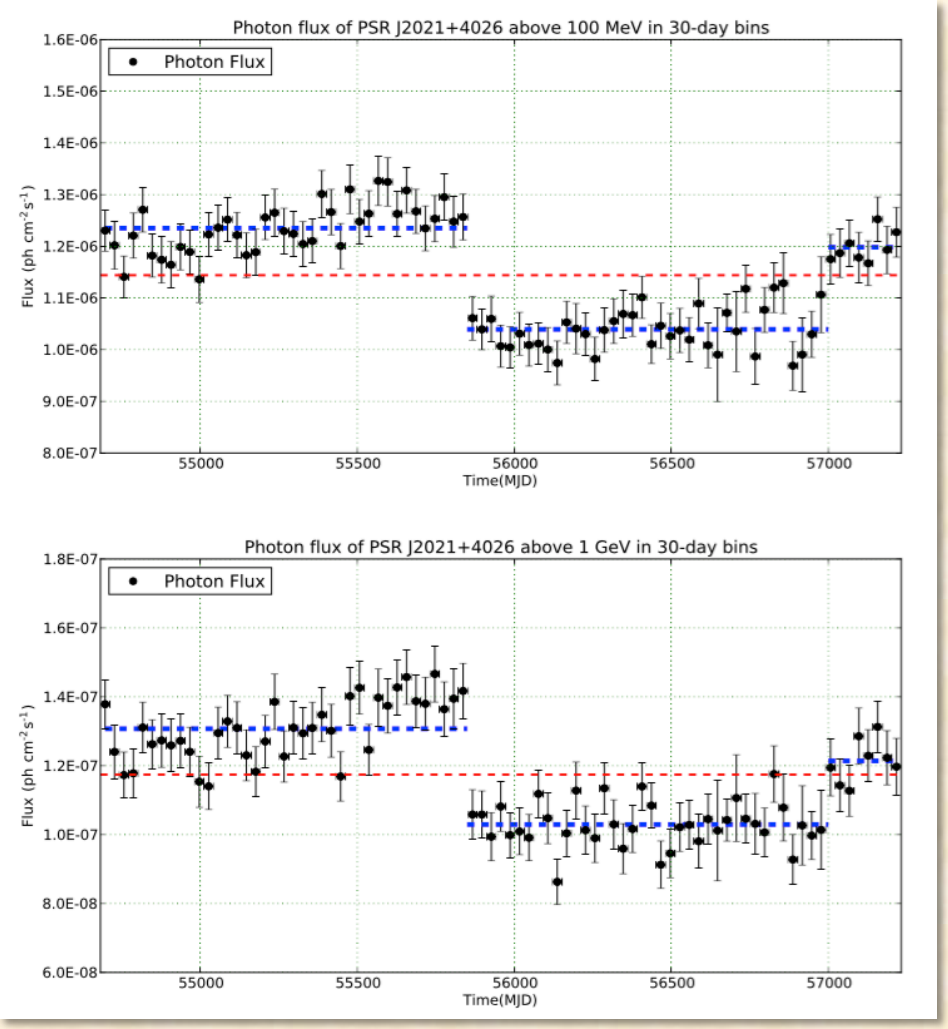




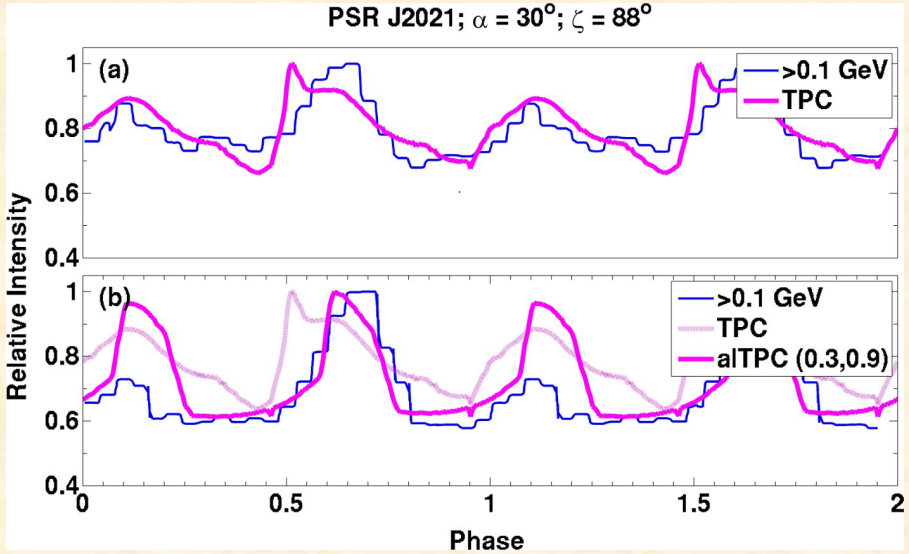
Change in pulse profile after change in $\dot{\nu}$

Spin-down state changes - γ-ray PSR J2021+4026

Now possibly returning to previous state (Ng et al. 2016)



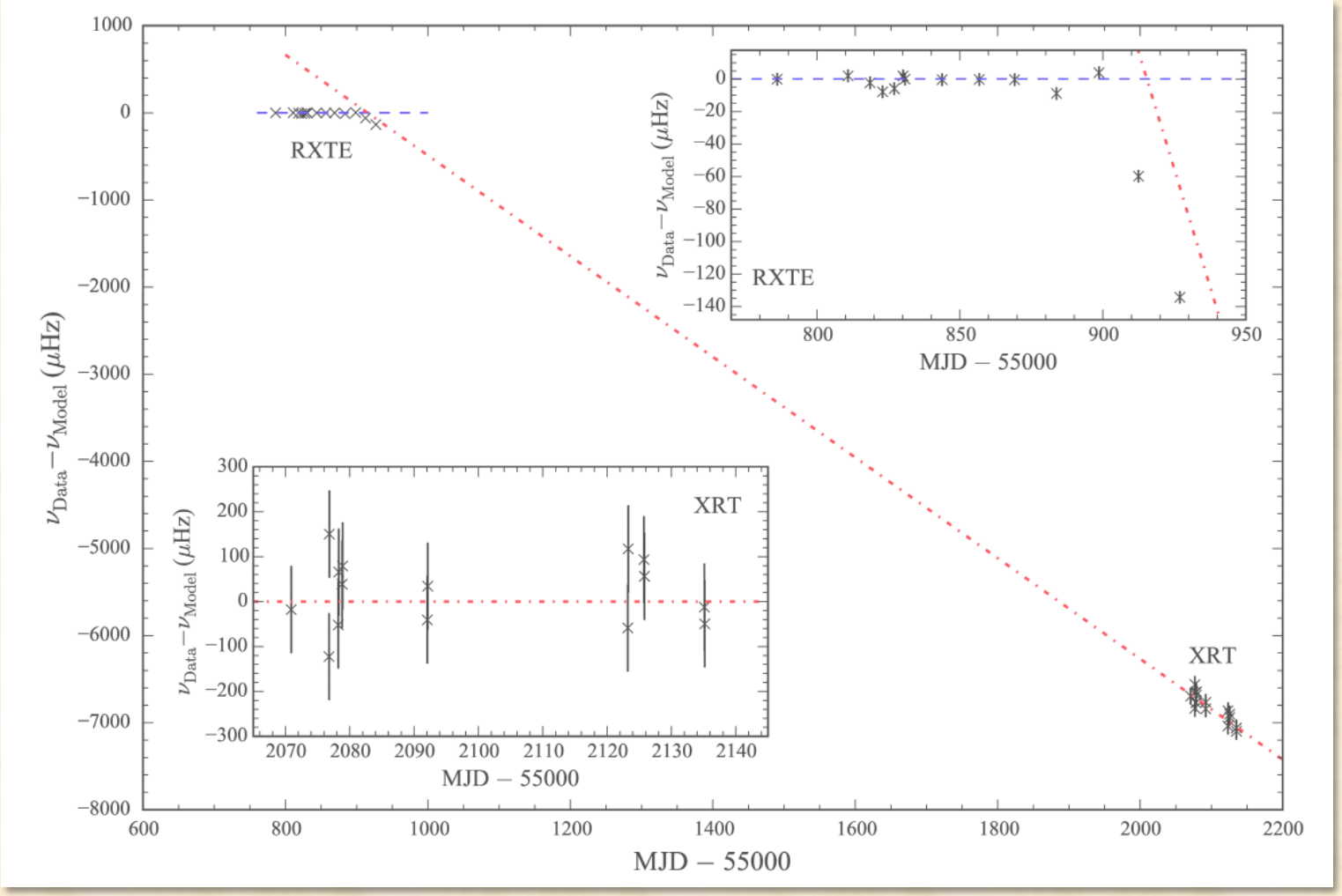
Light curve modeling before and after 1st state change – Emission moves higher in magnetosphere? (C. Venter)



Spin-down state changes – B0540-69

- 36% increase in spin-down rate
- No change in X-ray flux

Marshall et al. 2015



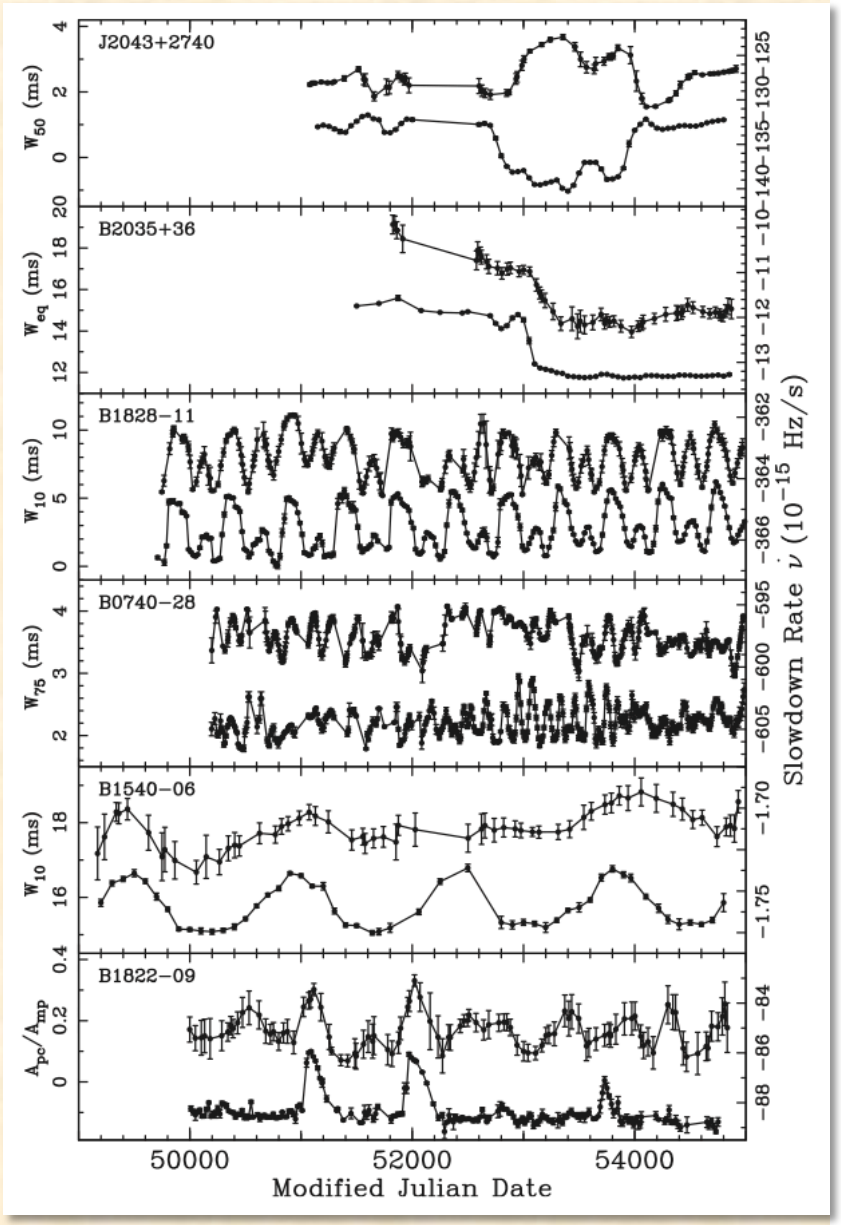
Spin-down state changes – radio pulsars

Lyne et al. 2010

- Correlated changes in pulse width and spin-down rate
- Pulsars fluctuate between two stable spin-down states on ~year timescales

$$\frac{\Delta\dot{\nu}}{\nu} \sim 0.3\% - 10\%$$

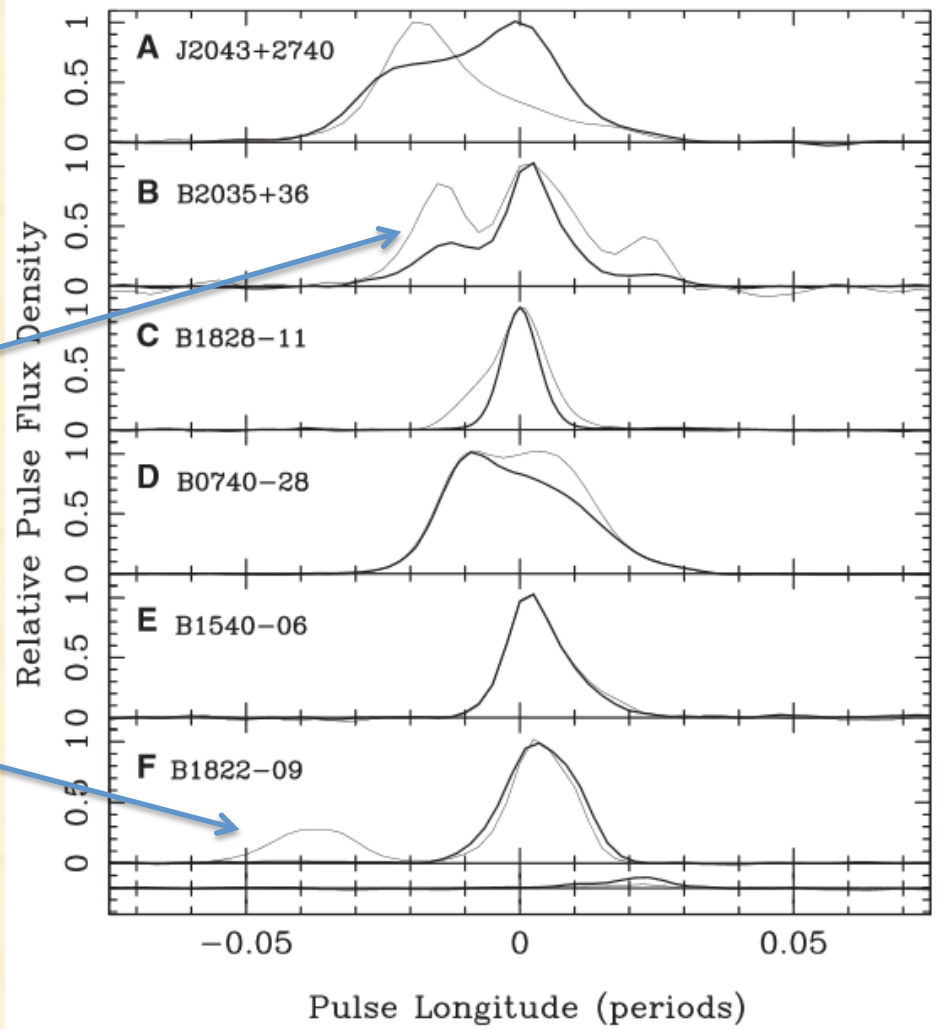
- Meta-stable states of magnetosphere/current flow?



Pulse profile and spin-down changes

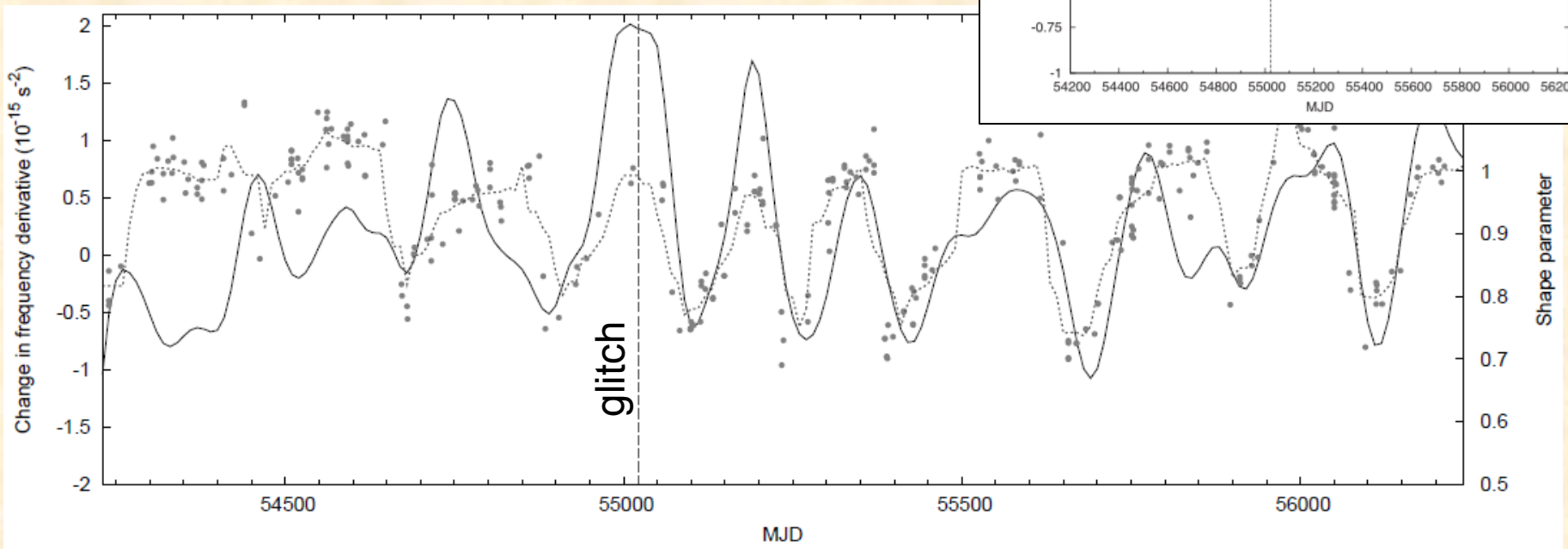
Lyne et al. 2010

- Darker/lighter profiles correspond to higher/lower $\dot{\nu}$ state
- Spin-down rate larger when core component of the radio profile is brighter
- In high $\dot{\nu}$ state, precursor is weaker and interpulse is stronger



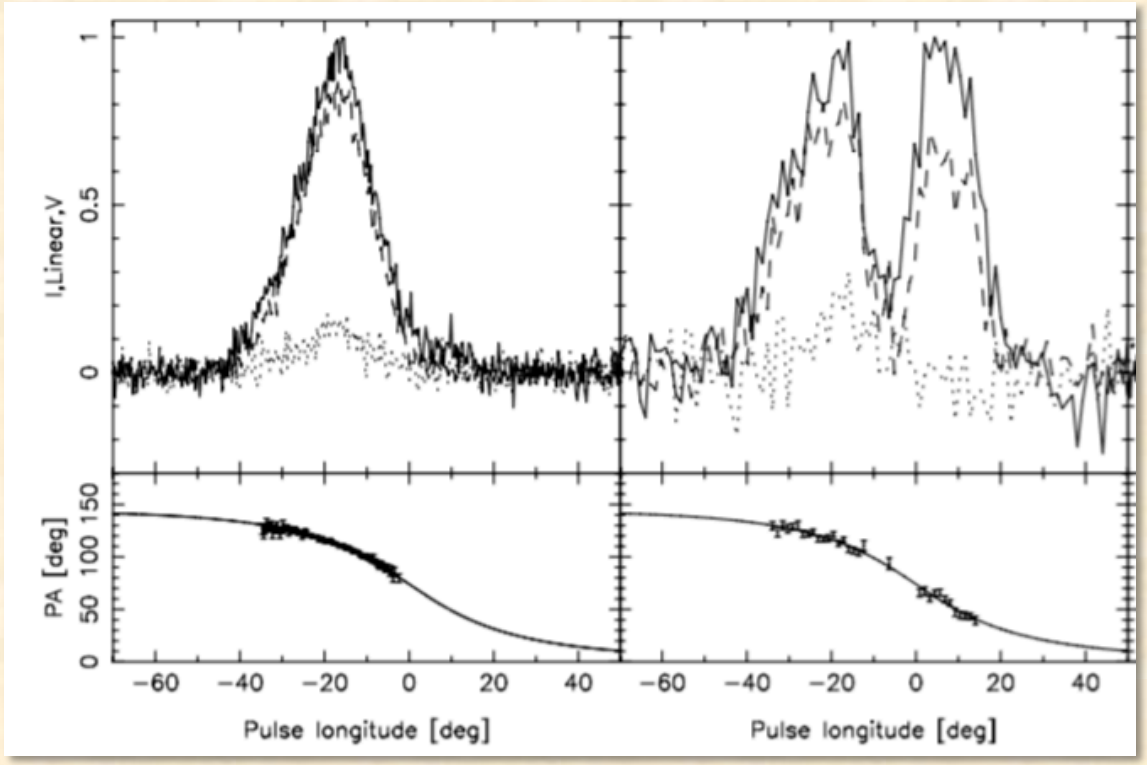
PSR B0740-28 – Link between magnetosphere and NS interior?

Profile shape and spin-down rate become stronger after glitch (Keith et al. 2013)

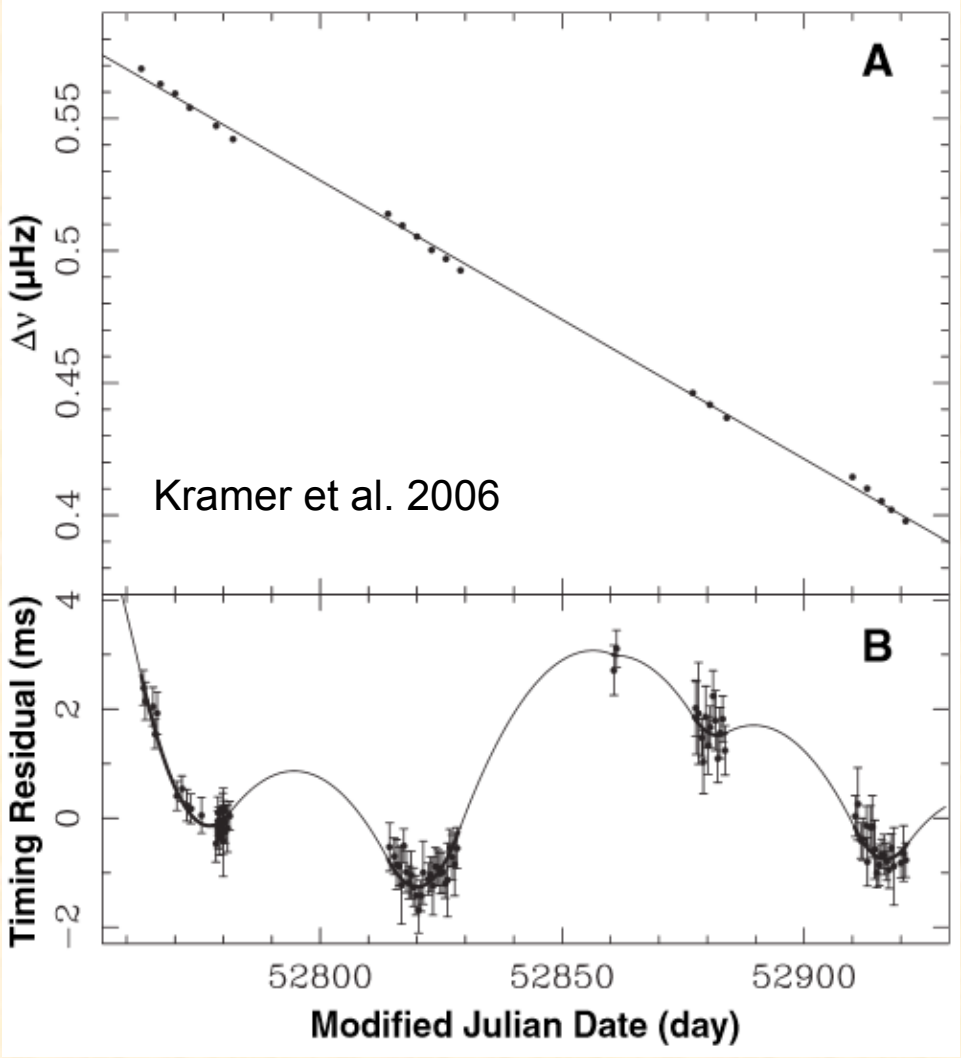


PSR J1119-6127 – profile change after a glitch

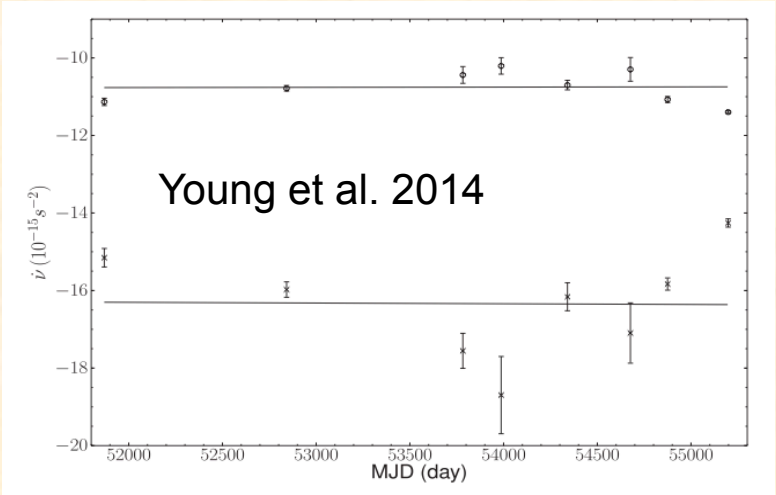
- Pulse profile changed from usual single to double following large glitch (Weltevrede et al. (2011)
- Post-glitch $\dot{\nu}$ smaller



Intermittent pulsars – B1931+24



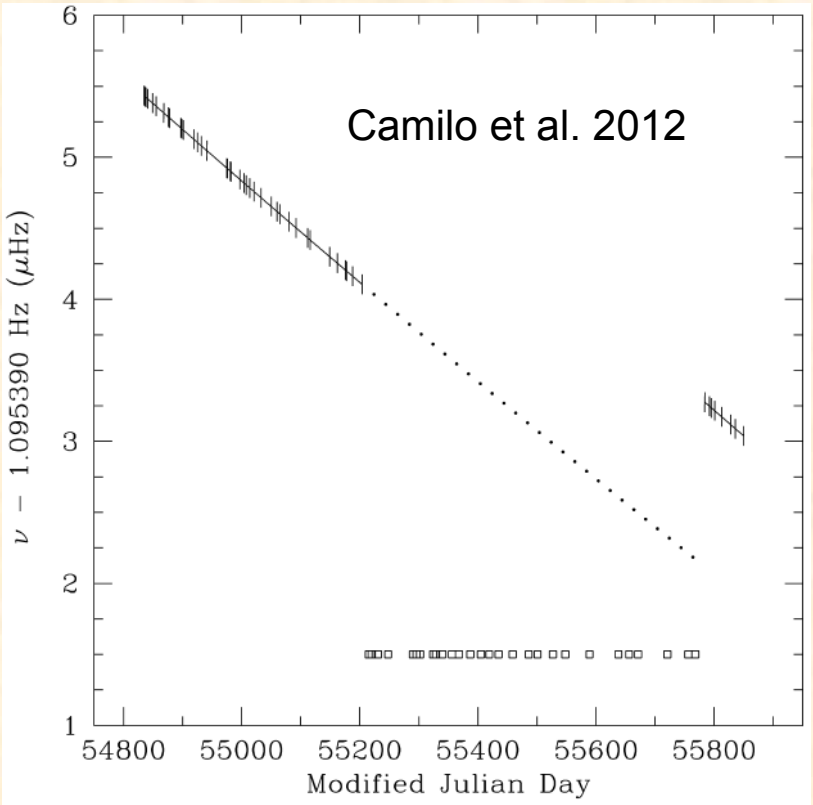
- Bimodal spin-down states
- Radio on/off states: larger/smaller spin-down rates – 3/2 ratio
- Different magnetosphere/ charge density states?
- Change it particle flux/ pulsar wind?

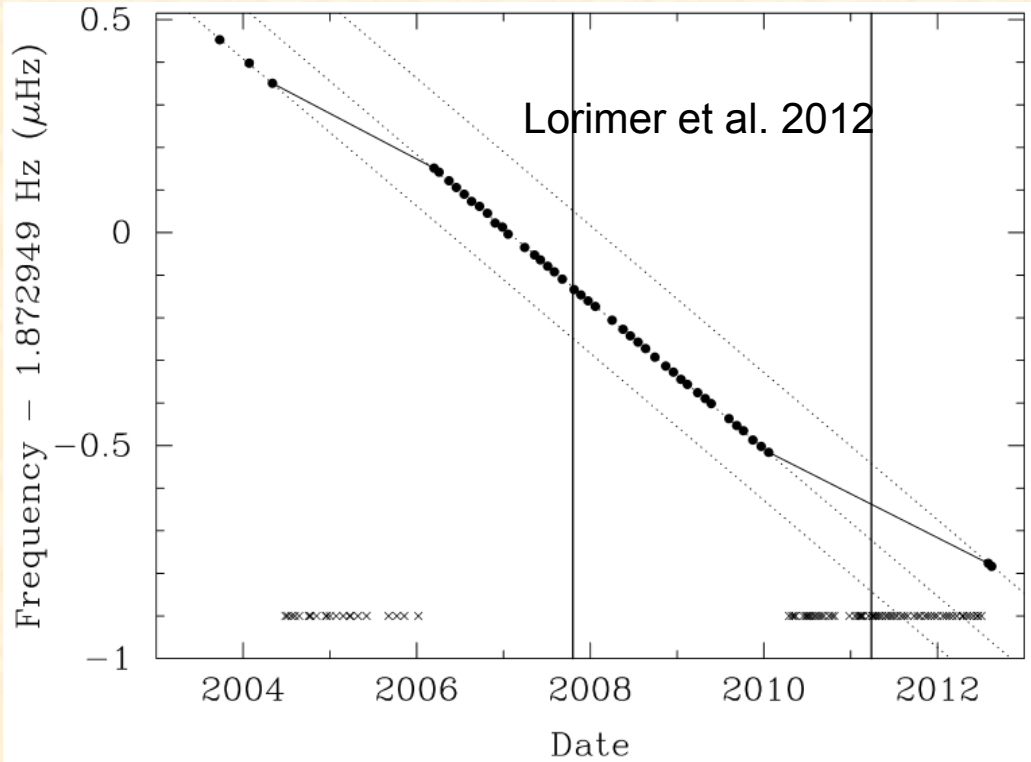


Intermittent pulsars – J1841-0500 and J1832+0029

J1841-0500: $\dot{\nu}_{\rm on} = 2.5\ \dot{\nu}_{\rm off}$

J1832+0029: $\dot{\nu}_{\rm on} = 1.8\ \dot{\nu}_{\rm off}$

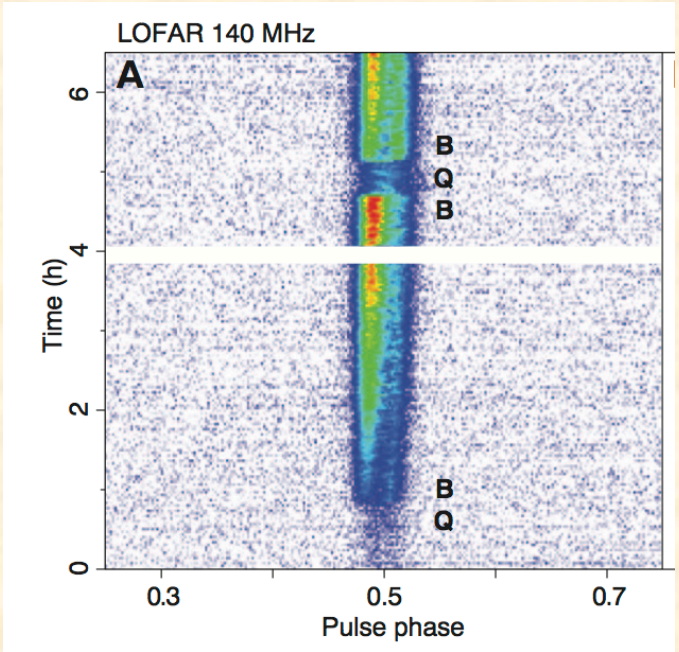


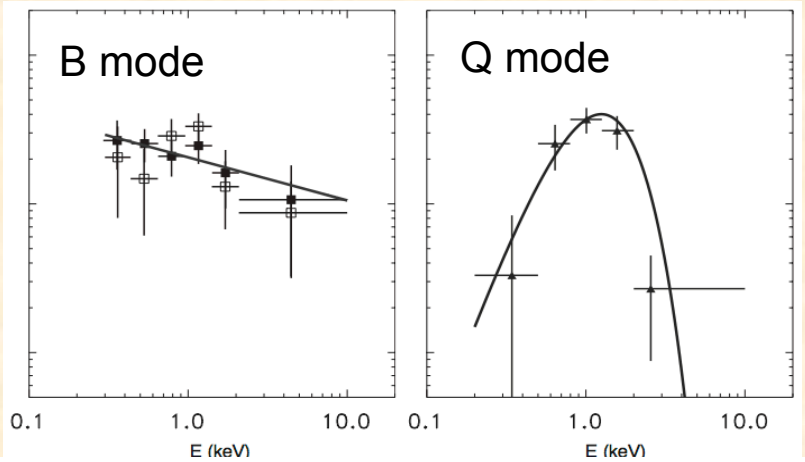


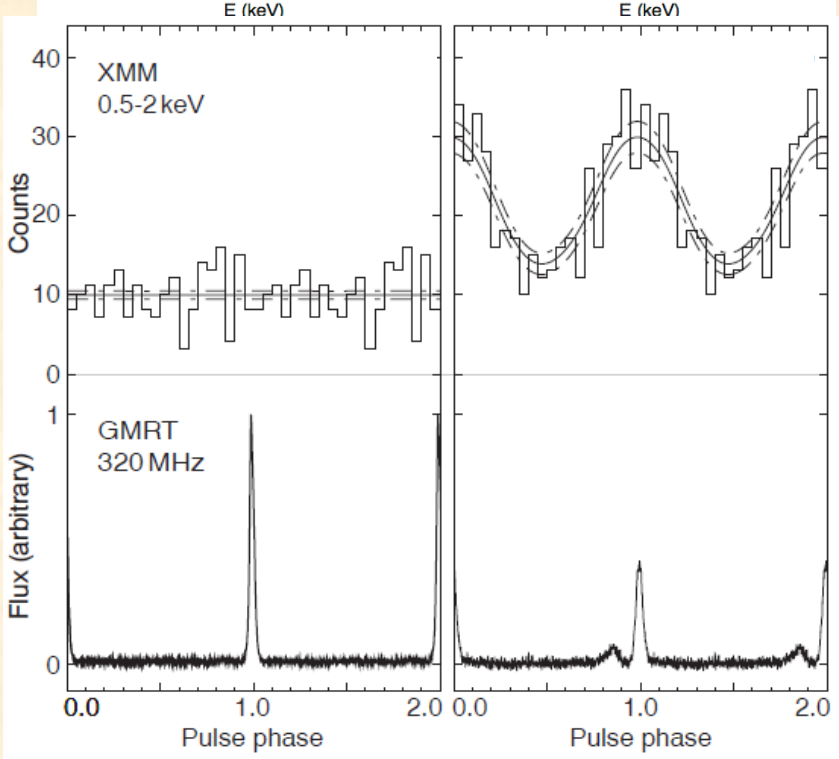
Multifrequency mode switching – B0943+10

Hermsen et al. 2013

- Simultaneous changes in radio and X-ray emission
- B mode: radio pulse bright: X-ray emission is unpulsed & mostly non-thermal or thermal (Mereghetti et al. 2013)
- Q mode: radio pulse weak: the X-ray emission shows an additional pulsed thermal component



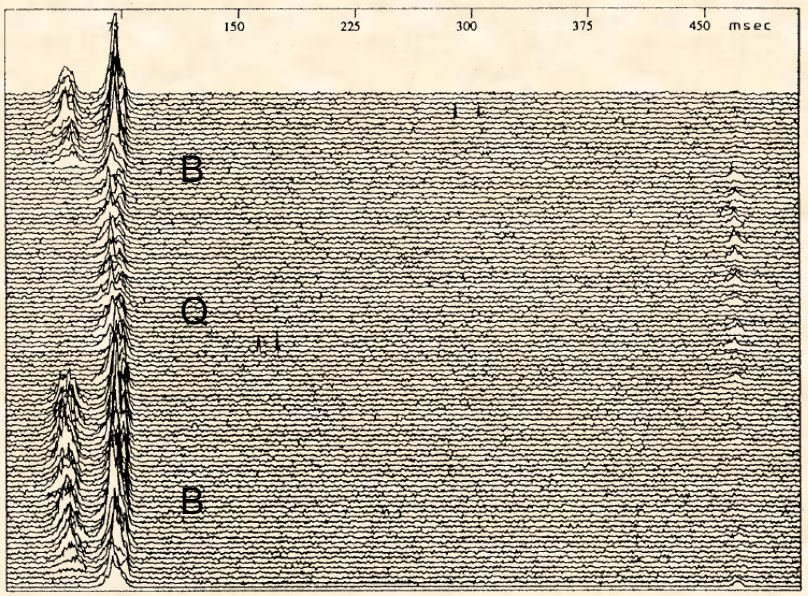




Inter-pole communication

B1055-52 and B1702-19: phase-locked flux modulation of MP and IP in phase delayed by 2.5P and 0.5P

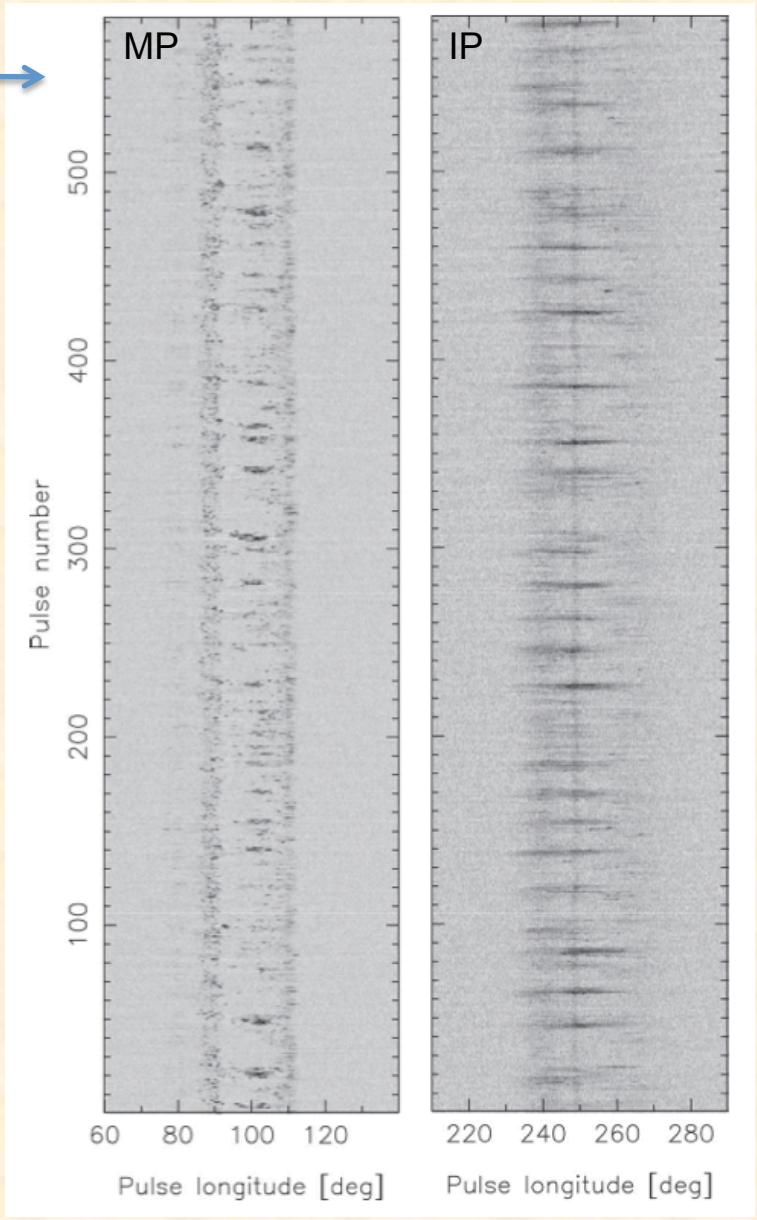
B1822-09: Coordinated mode switching - in Q mode IP turns on when MP component turns off !



Gil et al. 1994

How do poles communicate with each other?

Weltevrede et al. 2007, 2012

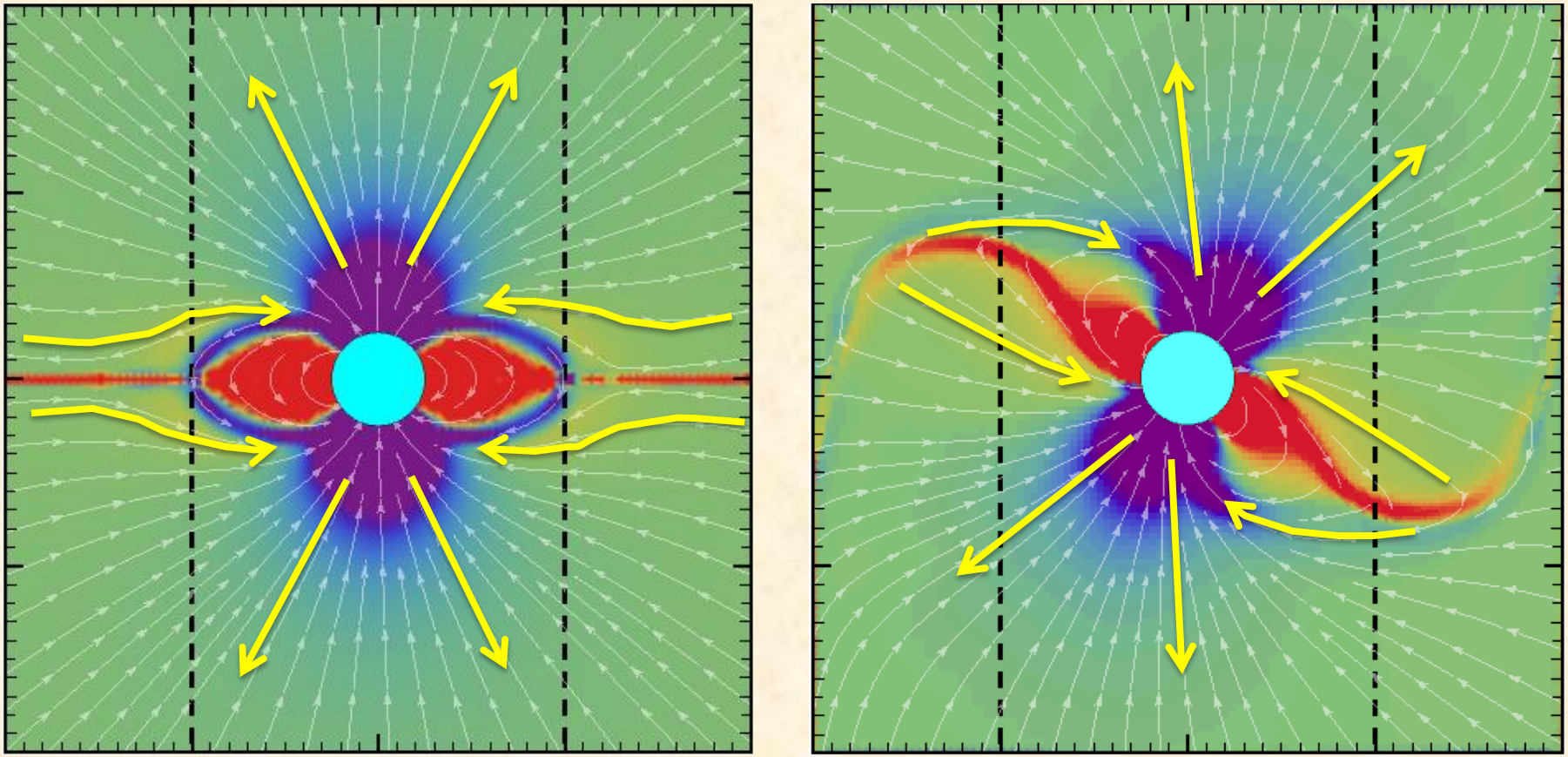


Global pulsar magnetospheres

Larger current flow ⟶ larger spin-down rate

(Harding et al. 1999)

$$T \approx \frac{2 I_{pc} B_0 R_{pc}^2}{3c}$$



Color: charge density, Streamlines: magnetic field

Resistive pulsar magnetospheres

Drift velocity

Conductivity

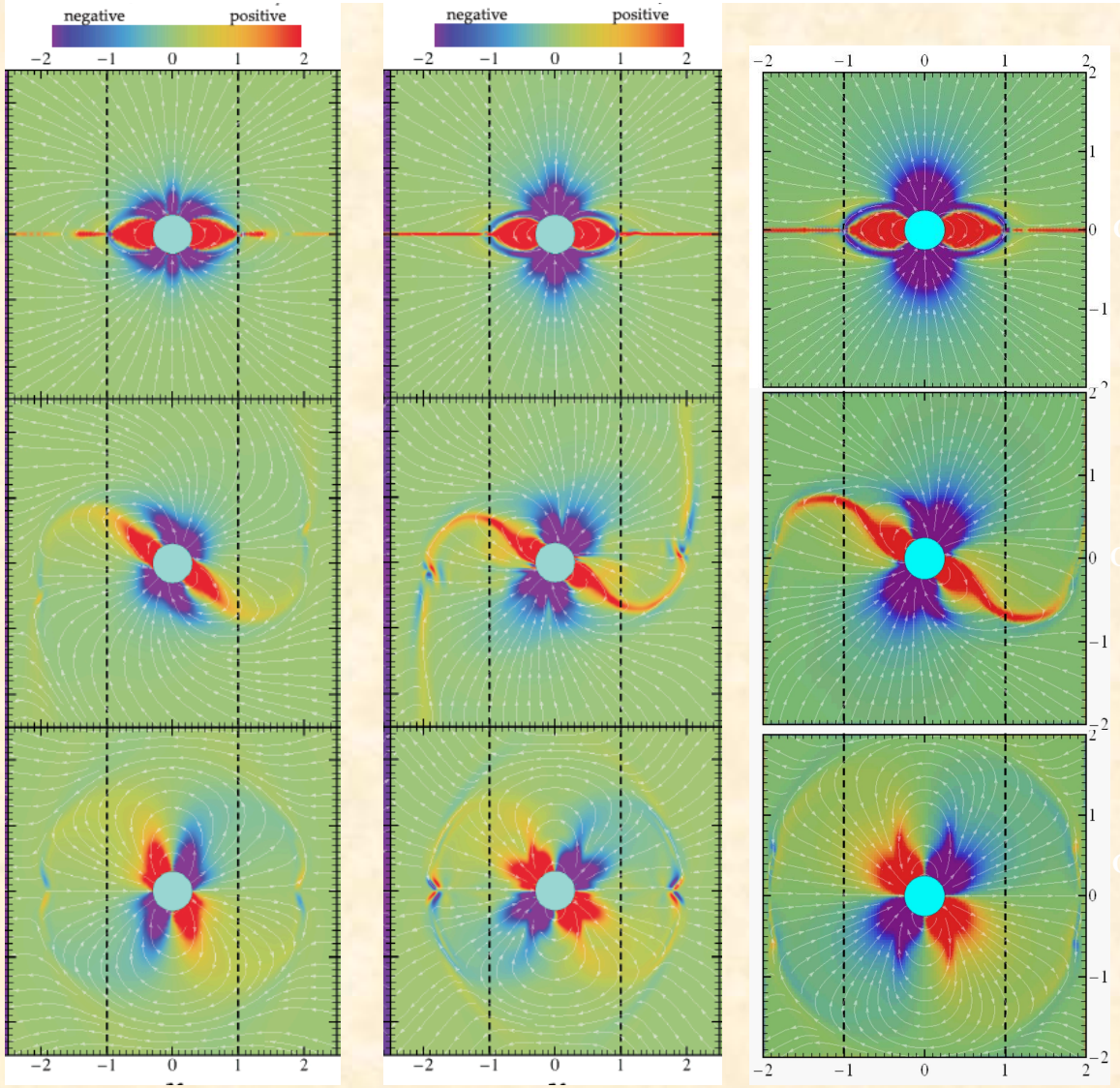
$$J = c\rho \frac{\mathrm{E} \times \mathrm{B}}{B^2 + E_0^2} + \sigma \, \mathrm{E}_{\parallel}$$

As conductivity increases:

- Charge and current density increase
- Current sheet gets stronger
- Field lines get straighter
- Spin-down power increases

Color: charge density, Streamlines: magnetic field

Low conductivity | Medium conductivity | Infinite conductivity (force free)



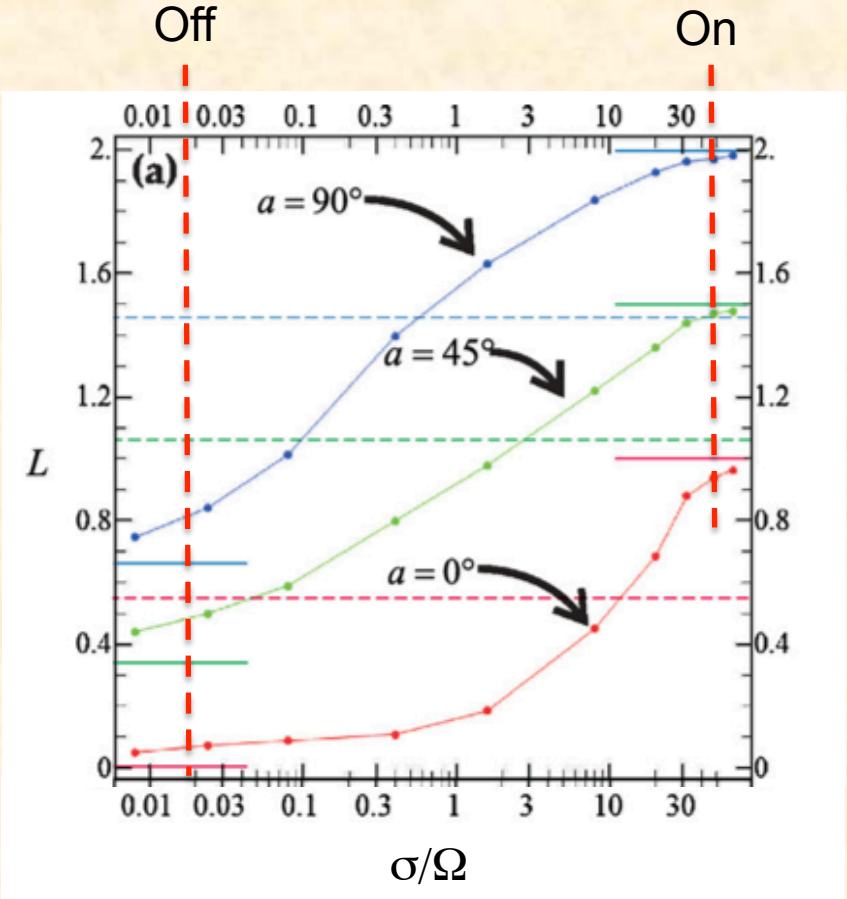
Kalapotharakos, Kazanas, Harding & Contopoulos 2012

Spin-down and magnetosphere conductivity

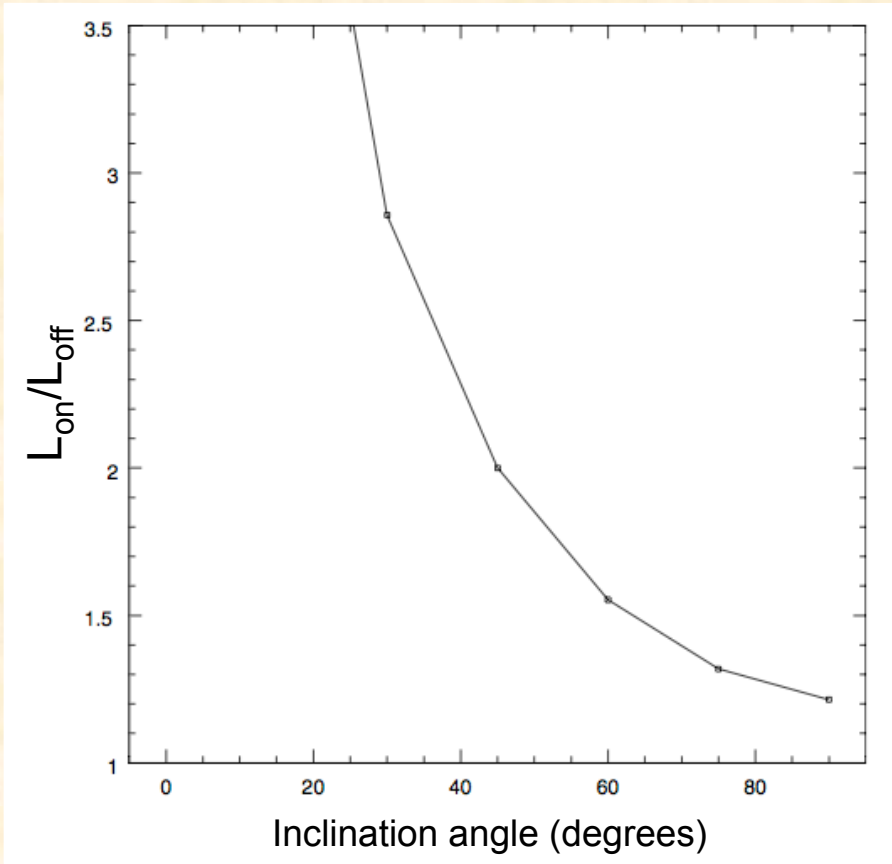
Intermittent pulsars:

- On state : high σ, near force-free
- Off state: low σ, near vacuum

$$L = 4\pi^2 I \frac{\dot{P}}{P^3}$$



Kalapotharakos, Kazanas, Harding & Contopoulos 2012



Li, Spitkovsky & Tchekhovskoy 2012

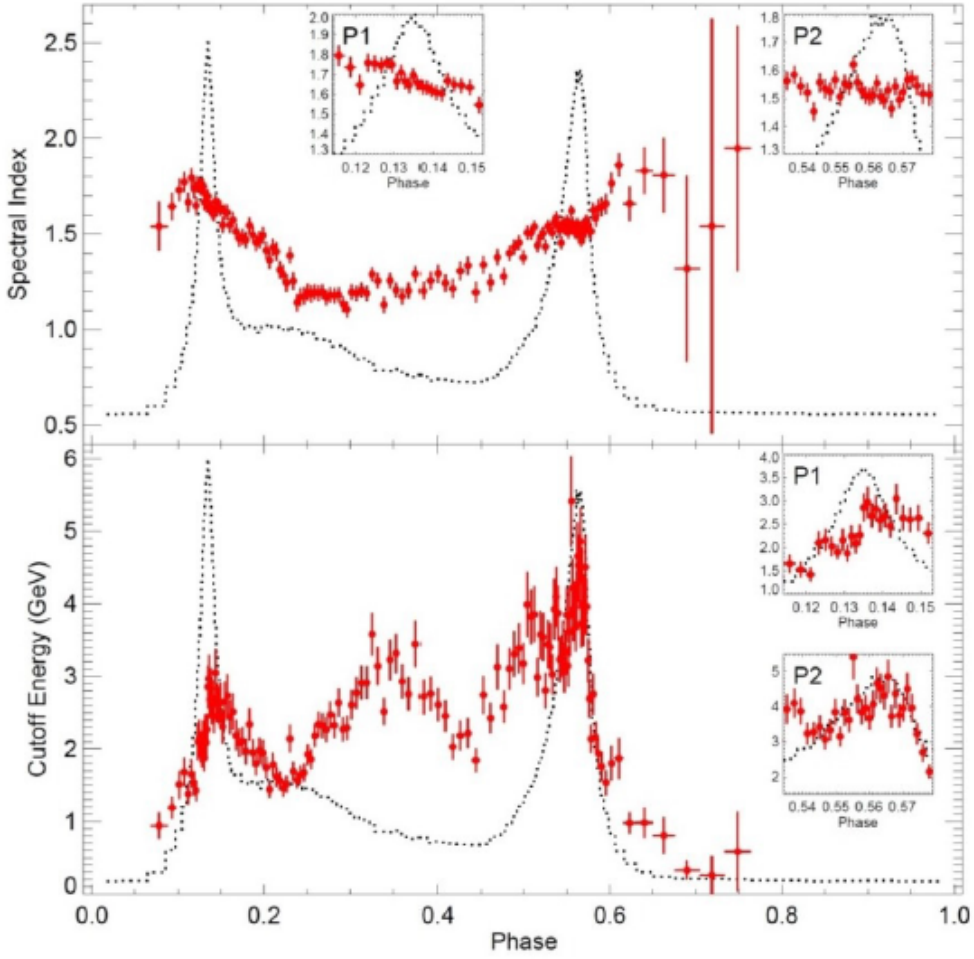
Conductivity and phase-resolved spectra

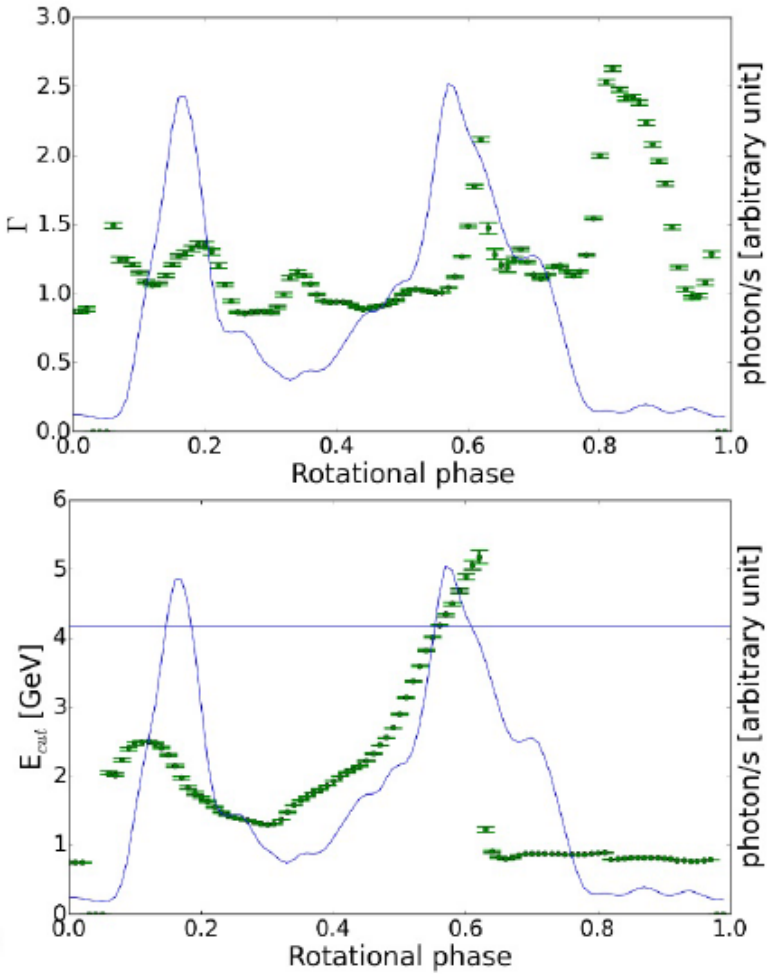
$$\frac{dN}{dE} \propto E^{-\Gamma} e^{-\frac{E}{E_{cut}}}$$

Matching dissipative models to Fermi light curves and spectra for 8 bright pulsars (Brambilla et al. 2015)

Observed

Model: $\alpha = 60^0$, $\zeta = 50^0$, $\sigma = 10\Omega$





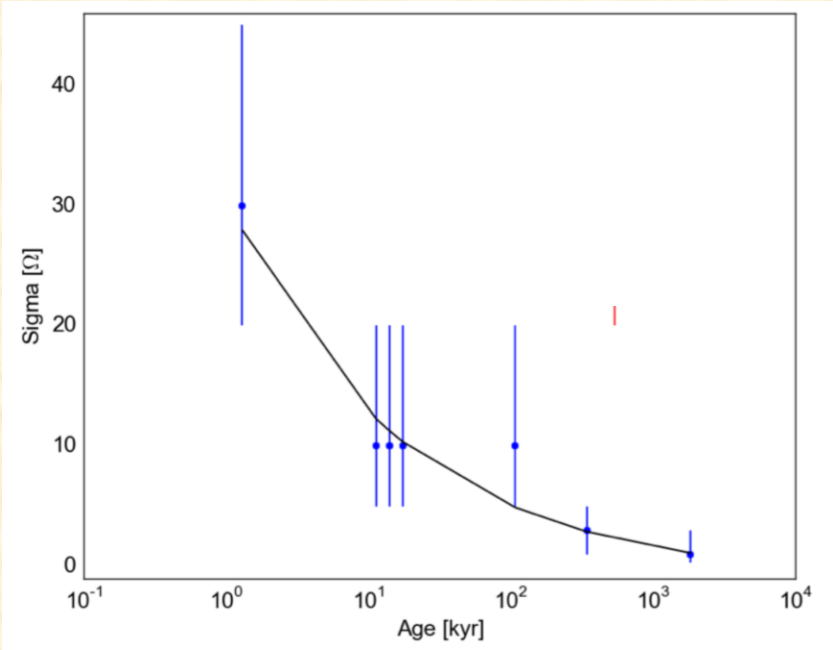
Decesar 2013

Brambilla et al. 2015

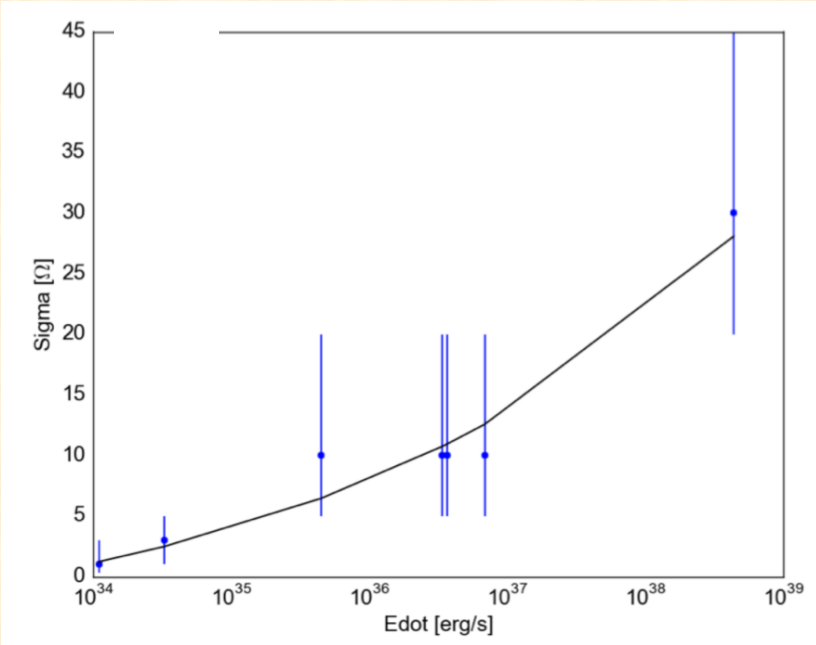
Trends with conductivity

The σ values that best describe each of the 8 bright pulsars (with published phase-resolved spectra) show an increase with the spin down rate $\dot{E}$ and a decrease with the pulsar age, expected if pair cascades are providing the magnetosphere conductivity (σ).

Age vs σ

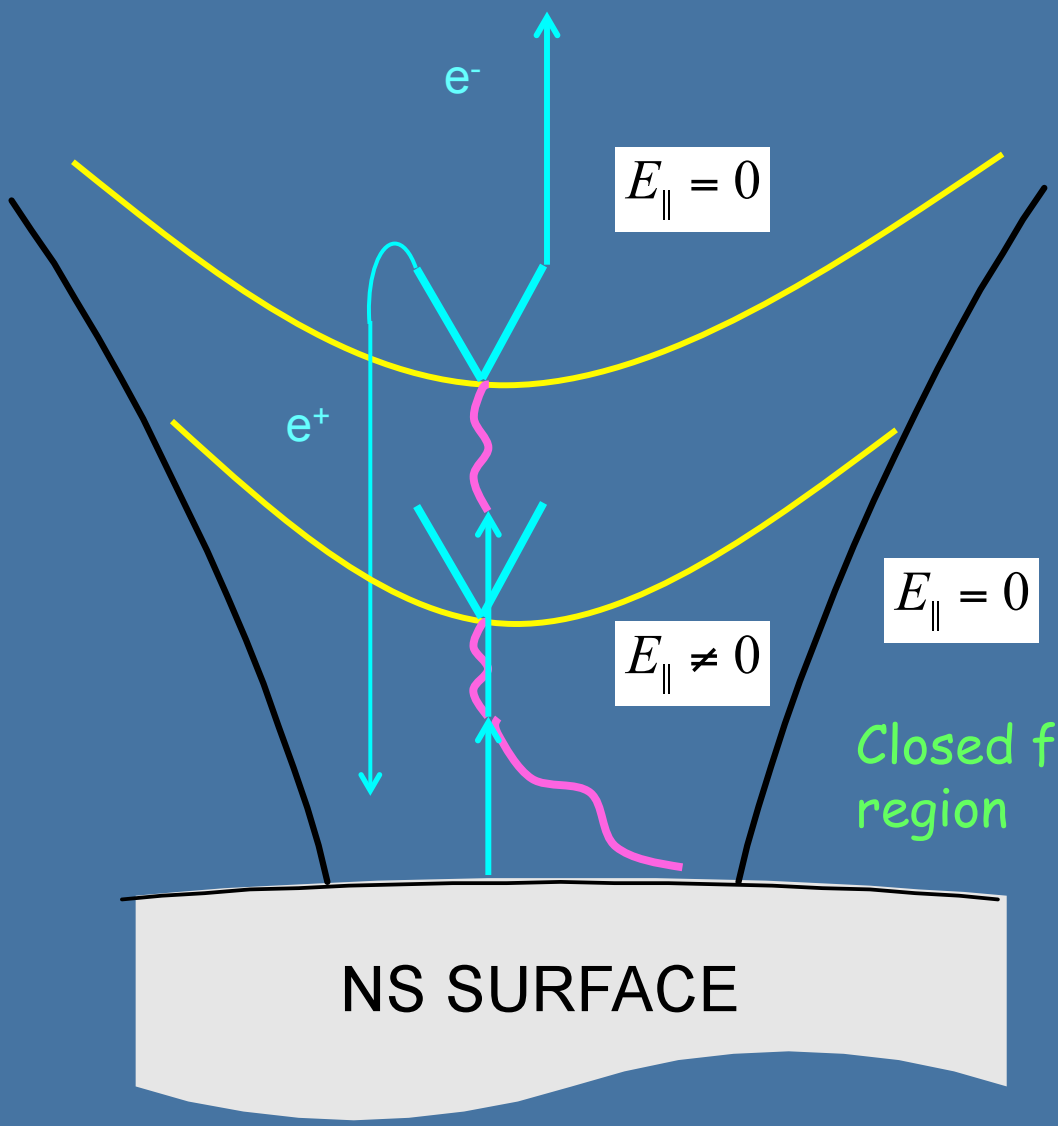


Spin-down rate vs σ



Brambilla et al. 2015

Modes of pair creation



Harding & Muslimov 1998

- **Curvature radiation pair front**

High pair multiplicity

complete screening

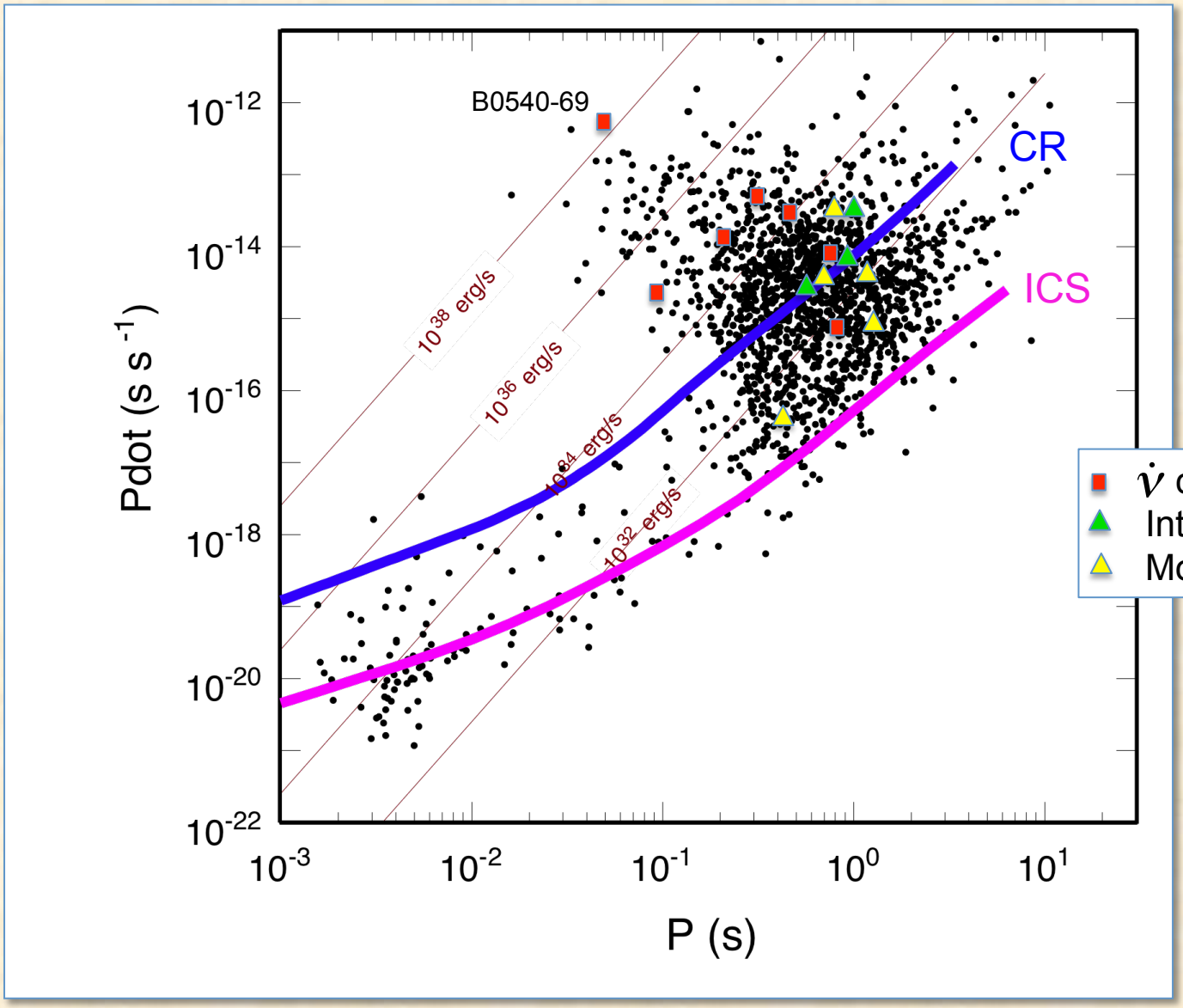
- **Inverse Compton scattering pair front**

Low pair multiplicity

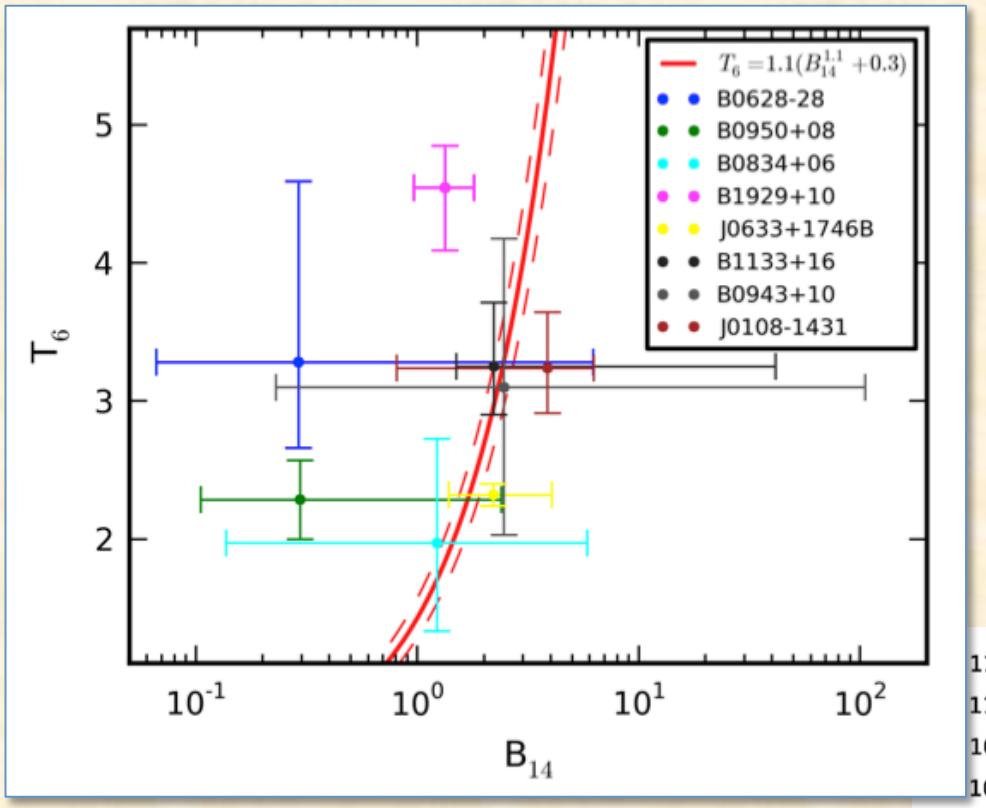
incomplete screening

Polar cap pair death lines

Harding & Muslimov 2002



Partially screened gaps

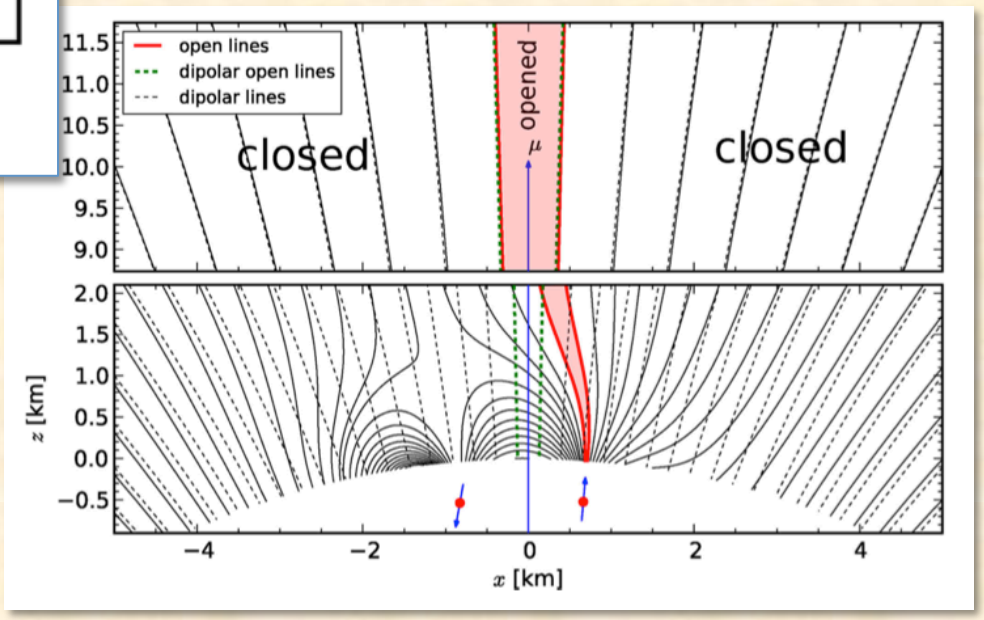


Szary et al. 2011

For high surface B, pulsars are near critical T for free surface emission

Switch between vacuum and partially screened gaps

Szary et al. 2015



Pair cascades vs. current

Sub-Goldreich-Julian currents – $0 < J/J_{GJ} < 1$

NO pair cascades

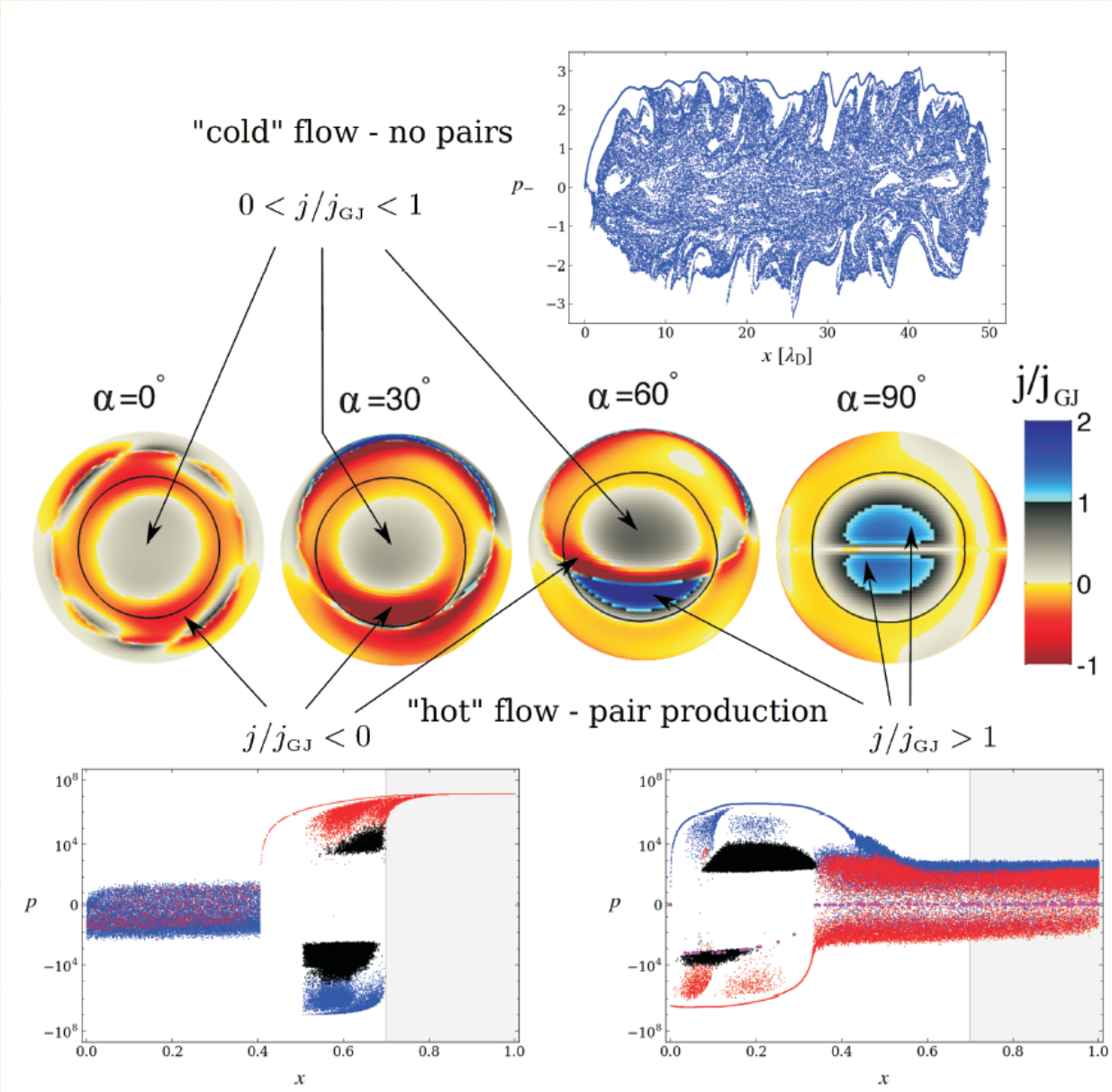
Super- Goldreich-Julian currents – $J/J_{GJ} > 1$

Pair cascades

Anti-Goldreich-Julian currents - $J/J_{GJ} > 0$

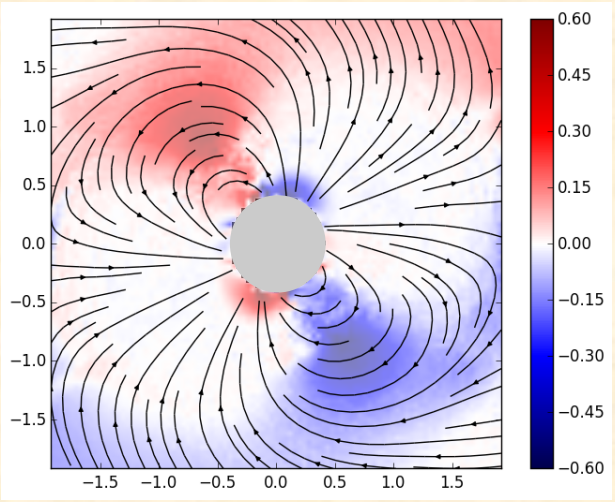
Pair cascades

Timokhin & Arons 2013



Pair modes and the global magnetosphere

Structure of magnetosphere and acceleration regions depends on rate of pair injection (conductivity)



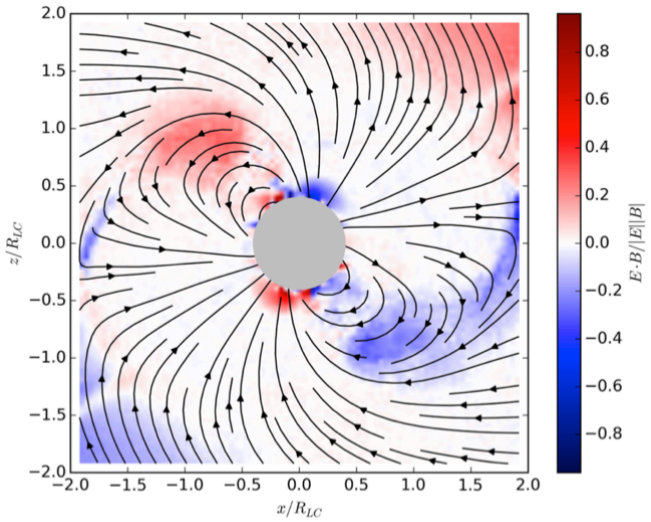
Particle-in-cell simulations:
Varying uniform injection of neutral plasma from 4, 8 and 16 particles per cell
Brambilla et al. 2015

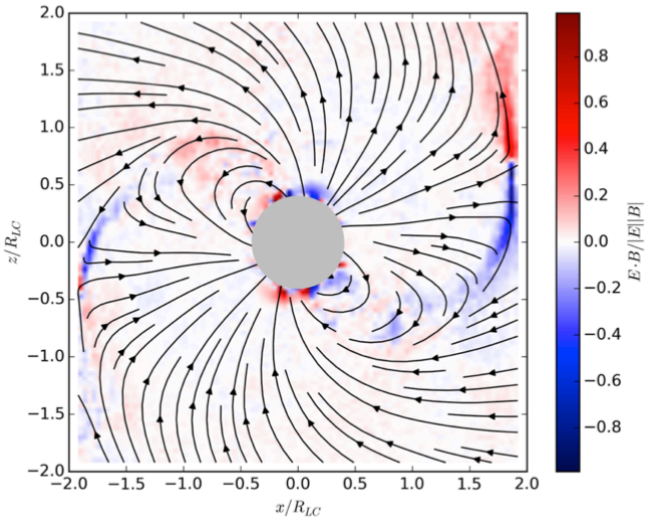
Near force-free

$E_{||}$ concentrates near current sheet

Near vacuum

$E_{||}$ (color) widespread
Field lines near dipole





Summary

- Spin-down changes, intermittency
  - Different magnetosphere states stable up to years
  - Global changes driven different conductivity (current, plasma injection)?
- Mode switching
  - Modes of polar cap pair creation (CR or ICS)?